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Photon-Induced Production of Mirror Quarks from LHT Model at LHC*

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Abstract *The photon-induced processes at the LHC provide clean experimental conditions due to absence of the proton remnants, which might produce complementary and interesting results for tests of the standard model and for searching of new physics. In the context of the littlest Higgs model with T-parity, we consider the photon-induced production of the mirror quarks at the LHC. The cross sections for various production channels are calculated and a simply phenomenological analysis is performed by assuming leptonic decays.*

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Key words: the mirror fermions, the LHT model, the LHC

1 Introduction

It is well known that the equivalent photon approximation (EPA) can be successfully used to describe most of the processes involving photon exchange.[1] A significant fraction of pp collisions at the LHC will involve quasi-real photon interactions occurring at energies well beyond the electroweak energy scale.[2] Therefore, the LHC can be considered as a high-energy photon-photon or photon-proton collider, which is paid significant attention recently.[3]

The photon-induced processes offer a rich and exciting field of research at the LHC.[3] In general, the exclusive two-photon production, $pp \to p\gamma\gamma p \to pXp$, provides clean experimental conditions and well defined final states, which can be selected and precisely reconstructed. Moreover, for the dedicated very forward detectors (VFDs), detection of the two final state protons, scattered at almost zero-degree angle, provides another striking signature, effective also at high luminosity and with large event pile-up.[2,4] Thus, the two-photon production of the charged particle pairs offers interesting potential for signals of new physics beyond the standard model (SM) at the LHC. It has been shown that detection of the supersymmetric charginos, sleptons, and the charged Higgs bosons is very unambiguous in two-photon exclusive production, allowing for clear interpretation.[5–6] The exclusive two-photon production of the boson pairs WW and ZZ at the LHC provides an excellent way to test the electroweak gauge boson sector.[7]

The luminosity and the center-of-mass (c.m.) energy of photon-proton (γp) collisions are higher than the photon-photon ones at the LHC. This offers interesting possibilities for the study of electroweak interactions and for searching the new physics beyond the SM up to TeV scale.[8] In contrast to the photon-photon production processes, the photoproduction processes involve topologies with hard jets in the final state. The effect of jet algorithms and the efficiency of event selection was taken into account using a fast simulation of a typical multipurpose LHC detector response.[8] Thus, a large number of $pp \to p(\gamma g/q)Y \to pXY$ processes have sizable cross sections and could be studied during the very low luminosity phases of the LHC. So far, the cross sections for many electroweak processes and some new physics processes with their irreducible background processes are studied in Refs. [7–9].

The little Higgs theory[10] is one of the interesting candidates of the new physics beyond the SM. The little Higgs model with T-patity (called the LHT model)[11] is one of the attractive little Higgs models. In this model, particles are divided into T-even and T-odd sectors under T-parity. The T-even sector consists of the SM particles and a heavy top T_+, while the T-odd sector contains heavy gauge bosons ($B_H, Z_H, W_H^{\pm}$), a scalar triplet (Φ), and the so-called mirror fermions. These new particles can produce rich phenomenology at present and in future high energy collider experiments.[12–16] Reference [17] has considered photoproduction of pairs of T-odd particles via e^+e^- and ep collisions. As we know, so far, photoproduction and two-photon production of the T-odd particles predicted by the LHT model have not been considered at the LHC, which is the main aim of this paper.

At the LHC, the mirror quarks can be pair produced or produced in association with other T-odd particles via quark-quark, gluon-gluon, or quark-gluon fusion, which have extensively studied in Ref. [13]. Their production cross sections are at the orders of 10^{-1} fb–10^4 fb in most of the parameter space of the LHT model. The production cross sections for the photoproduction and two-photon production processes involved the mirror quarks at the LHC are generally smaller than those coming from these partonic processes. However, considering their clean experimental conditions and well defined final states, the photoproduction and two-photon production processes for the mirror quarks might help to search possible signatures

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of the LHT model at the LHC. Thus, these production processes should be further studied.

In the rest of this paper, we will give our results in detail. In Sec. 2, we briefly review the essential features of the LHT model. Photoproduction of the mirror quark associated with a new gauge boson and with a new scalar are discussed in Secs. 3 and 4, respectively. The cross sections for photoproduction and two-photon production of the mirror quark pairs are calculated in Sec. 5. The simply phenomenological analysis at the LHC are also given in these sections. Finally, we summarize our results and give some discussions in Sec. 6.

2 Essential Features of LHT Model

In this section, we briefly review the essential features of the LHT model studied in Refs. [11–12], which are related to our calculation. The LHT model is based on a SU(5)/SO(5) global symmetry breaking pattern, which gives rise to fourteen Numbu–Goldstone (NG) bosons. Four of the fourteen NG bosons are eaten by the T-odd heavy gauge bosons $(B_H, Z_H, W_H^{\pm})$ associated with the gauge symmetry breaking $[\mathrm{SU}(2)\times \mathrm{U}(1)]_1 \times [\mathrm{SU}(2)\times \mathrm{U}(1)]_2 \to \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ at the scale f. The remaining NG bosons decompose into a T-even doublet H, considered to be the SM Higgs doublet, and a complex T-odd SU(2) triplet Φ

$$H = \begin{pmatrix} -i\dfrac{\pi^+}{\sqrt{2}} \\ \dfrac{\nu + h + i\pi^0}{2} \end{pmatrix},$$

$$\Phi = \begin{pmatrix} -i\phi^{++} & -i\dfrac{\phi^+}{\sqrt{2}} \\ -i\dfrac{\phi^+}{\sqrt{2}} & \dfrac{-i\phi^0 + \phi^P}{\sqrt{2}} \end{pmatrix}. \tag{1}$$

Here h is the physical Higgs field and $\nu = 246$ GeV is the electroweak scale. The NG bosons $\pi^{0,\pm}$ are absorbed by the SM gauge bosons $W^{\pm}$ and Z after electroweak symmetry breaking (EWSB). There is a relation between the T-odd triplet and the T-even Higgs boson masses, which is approximately expressed as[12]

$$M_\Phi = \frac{\sqrt{2}m_H}{\nu} f\,, \tag{2}$$

where f is the scale parameter of the gauge symmetry breaking of the LHT model. At the leading order, the components ϕ^+, ϕ^-, ϕ^0, and ϕ^p of the triplet scalar Φ have same mass, i.e. $M_{\phi^+} = M_{\phi^-} = M_{\phi^0} = M_{\phi^p} = M_\Phi$.

After taking into account EWSB, at the order of ν^2/f^2, the masses of the T-odd set of the SU(2) $\times$ U(1) gauge bosons are given by

$$M_{B_H} = \frac{g'f}{\sqrt{5}}\Big[1 - \frac{5\nu^2}{8f^2}\Big],$$

$$M_{Z_H} \approx M_{W_H} = gf\Big[1 - \frac{\nu^2}{8f^2}\Big], \tag{3}$$

where g' and g are the SM $\mathrm{U}(1)_Y$ and $\mathrm{SU}(2)_L$ gauge coupling constants, respectively. Because of the smallness of g', the gauge boson B_H is the lightest T-odd particle, which is stable, electrically neutral, and weakly interacting particle. Thus, it can be seen as an attractive dark matter candidate.[12] Certainly, if the T-parity is violated by anomalies, the lightest T-odd gauge boson B_H can decay into the SM gauge boson pairs WW and ZZ.[18–19]

To avoid severe constraints and simultaneously implement T parity, one needs to double the SM fermion doublet spectrum.[11–12] The T-even combination is associated with the SM $\mathrm{SU}(2)_L$ doublet, while the T-odd combination is its T-parity partner, which are called the mirror fermions. Assuming there is flavor universal and diagonal Yukawa coupling k, the mirror quarks for different generations will be degenerate in mass, and the masses of the up- and down-type mirror fermions can be written as[13]

$$M_{U_H} \approx \sqrt{2}kf\Big(1 - \frac{\nu^2}{8f^2}\Big), \quad M_{D_H} \approx \sqrt{2}kf\,. \tag{4}$$

Being $f \geq 500$ GeV, it is clear from Eq. (4) that there is $M_{U_H} \approx M_{D_H}$. Thus, we can assume the mirror quarks degenerating in mass and take $M_{Q_H} = M = \sqrt{2}kf$. This means that the mirror quarks have no contributions to the flavor changing processes, which is the minimal flavor violation (MFV) limit of the LHT model.[20] In this paper, we will focus our attention on production of the first and second generation mirror quarks via photon interactions at the LHC and assume that the value of the coupling constant k is in the range of 0.5–1.5.

The mirror quarks can couple to ordinary quarks by emitting T-odd gauge bosons and by emitting the scalar triple Φ at higher order, which are parameterized by two CKM-like unitary mixing matrices V_{Hu} and V_{Hd}. They satisfy $V_{\mathrm{Hu}}^{+}V_{\mathrm{Hd}} = V_{\mathrm{CKM}}$, in which the CKM matrix is defined through flavor mixing in the down-type quark sector.[15,20] The coupling expressions, which are related to our calculation, are given in Ref. [15]. Using these Feynman rules, we can calculate the production cross sections of the mirror quarks via γp and $\gamma\gamma$ collisions at the LHC.

From the above discussions, we can see that the cross sections for photoproduction and two-photon production of the mirror quarks are generally dependent on the model parameters f, k, $(V_{\mathrm{Hu}})_{ij}$, and $(V_{\mathrm{Hd}})_{ij}$. The matrix V_{Hd} can be parameterized in terms of three mixing angles and three phases, which can be probed by the flavor changing neutral current (FCNC) processes in K and B meson systems, as discussed in detail in Refs. [15, 20]. To avoid any additional free parameters introduced and to simplify our calculation, we take the structure of the mixing matrix V_{Hd} as $V_{\mathrm{Hd}} = I$, which means $V_{\mathrm{Hu}} = V_{\mathrm{CKM}}^{+}$ and the mirror quarks have no impact on the FCNC processes.

3 Photoproduction of Mirror Quark Associated with a *T*-odd Gauge Boson

From the above discussions, we can see that the mirror quark can be produced associated with a T-odd gauge boson via the subprocess $q\gamma \to Q_H B_H$ (Z_H or W_H) at the LHC. The relevant Feynman diagrams are depicted in Fig. 1.

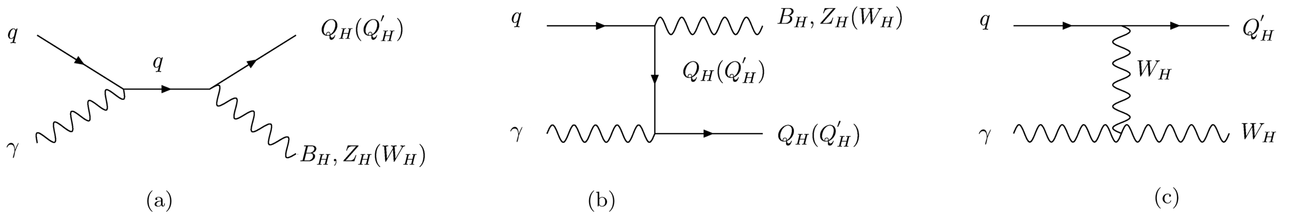

Fig. 1 Feynman diagrams for photoproduction of the mirror quark associated with a T-odd gauge boson.

Using the relevant Feynman rules given in Ref. [15], the corresponding scattering invariant amplitudes can be written as

$$M_B^{ij} = -\frac{i}{10}\frac{e^2}{C_W}q^i V_{ij}\bar{u}(P_Q)\Big[\frac{\not\varepsilon_2 P_L(\not P_\gamma + \not P_q)\not\varepsilon_1}{\hat{s}} + \frac{\not\varepsilon_1(\not P_B - \not P_q + M)\not\varepsilon_2 P_L}{\hat{t}_B - M^2}\Big]u(P_q)\,, \tag{5}$$

$$M_Z^{ij} = \pm\frac{i}{2}\frac{e^2}{S_W}q^i V_{ij}\bar{u}(P_Q)\Big[\frac{\not\varepsilon_2 P_L(\not P_\gamma + \not P_q)\not\varepsilon_1}{\hat{s}} + \frac{\not\varepsilon_1(\not P_Z - \not P_q + M)\not\varepsilon_2 P_L}{\hat{t}_Z - M^2}\Big]u(P_q)\,, \tag{6}$$

$$M_W^{ij} = \frac{i}{\sqrt{2}}\frac{e^2}{S_W}V_{ij}\bar{u}(P_Q)\Big\{\frac{\not\varepsilon_2 P_L(\not P_\gamma + \not P_q)\not\varepsilon_1 q^i}{\hat{s}} + \frac{\not\varepsilon_1(\not P_W - \not P_q + M)\not\varepsilon_2 P_L q^i}{\hat{t}_W^1 - M^2}$$
$$+ \frac{\not\varepsilon_2 P_L[g^{\mu\rho}P_\gamma^\sigma + g^{\mu\sigma}(P_Q - P_q - P_r)^\rho + g^{\rho\sigma}(P_q - P_Q)^\mu]}{\hat{t}_W^2 - M_{W_H}^2}\Big\}u(P_q)\,, \tag{7}$$

where $\hat{s} = (P_\gamma + P_q)^2$, $\hat{t}_B = (P_B - P_q)^2$, $\hat{t}_Z = (P_Z - P_q)^2$, $\hat{t}_W^1 = (P_W - P_q)^2$, and $\hat{t}_W^2 = (P_Q - P_q)^2$. i represents the SM light quark u, c, d, or s, and q^i represents the corresponding electric charge. j is the family indexes for the mirror quarks and M is the mass of the mirror quark. $S_W = \sin\theta_W$, $C_W = \cos\theta_W$, and θ_W is the Weinberg angle. ε_1 is the polarization vector of the photon γ and ε_2 is the polarization vector of the gauge boson Z_H, B_H, or W_H. $P_L = (1-\gamma_5)/2$ is the left-handed projection operator. For the up-type quark u or c, the CKM-like matrix element V_{ij} is $(V_{Hu})_{ij}$, while for the down-type quark d, s, or b, V_{ij} is $(V_{Hd})_{ij}$. In Eq. (6), "±" represent the up- and down-type quarks, respectively.

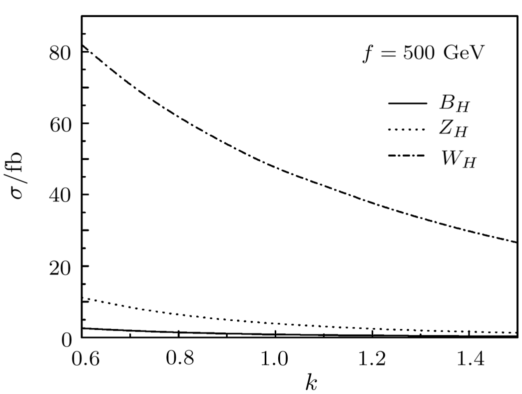

Fig. 2 The cross sections for the photoproduction of the mirror quarks associated with the new gauge bosons (B_H, Z_H, W_H) as functions of the coupling constant k for the scale parameter $f = 500$ GeV.

After calculating the cross section $\hat{\sigma}_G^{ij}(\hat{s})$ ($G = Z_H$, B_H, or W_H) for the subprocess $q\gamma \to Q_H B_H$ (Z_H or W_H), the effective cross section σ_G at the LHC can be obtained by folding $\hat{\sigma}_G^{ij}(\hat{s})$ with the parton distribution functions (PDFs)

$$\sigma_G = \sum_{i,j}\int_{x_{\min}}^{1}\int_{\tau_{\min}}^{\tau_{\max}} dx d\tau f_{q_i/p}(x,\mu) f_{\gamma/p}(\tau)\hat{\sigma_G}^{ij}(\hat{s}) \tag{8}$$

with $x_{\min} = (M_Q + M_G)^2/S$, $\tau_{\min} = (M_Q + M_G)^2/Sx$, $\tau_{\max} = (1 - m/\sqrt{S})^2$, and $\hat{s} = x\tau S$, in which the c.m. energy $\sqrt{S}$ is taken as 14 TeV for the LHC. m is the proton mass. In our numerical calculation, we will use CTEQ6L PDF[21] for the quark distribution $f_{q_i/p}(x,\mu_F)$ and assume that the factorization scale μ_F is of order $\sqrt{\hat{s}}$. The photon distribution function $f_{\gamma/p}(\tau)$ is assumed that it only is the elastic components of the equivalent photon distribution of the proton, which has been extensively studied in Refs. [1, 22–23]. Its concrete expression is lengthy, which has been given in literature, for example in Refs. [1] and [23]. So, we will not present it here.

In Figs. 2, 3(a), and 3(b) we plot the cross sections for photoproduction of the mirror quark associated with a T-odd gauge boson as functions of the parameter k for three values of the scale parameter f. In these three figures we have taken the values of the CKM matrix elements $(V_{\rm CKM})_{ij}$ given in Ref. [24], in which $V_{\rm CKM}$ is constructed based on the parameterization.[25] One can see from these figures that, although there is the relation $M_{B_H} < M_{Z_H} \simeq M_{W_H}$, the cross section σ_{B_H} is smaller than σ_{W_H} or σ_{Z_H}. This is because the coupling constants of the new gauge boson B_H to the mirror quarks and ordinary quarks are smaller than those for the new gauge bosons Z_H and W_H. Furthermore, for the subprocess $q\gamma \to Q'_H W_H$, there is an extra Feynman diagram as shown in Fig. 1(c) contributing to the cross section σ_{W_H}. For $0.6 \le k \le 1.4$ and 500 GeV $\le f \le$ 1500 GeV, the values of the effective production cross sections σ_{B_H}, σ_{Z_H} , and σ_{W_H} are in the ranges of 1.6×10^{-2} fb–2.6 fb, 7.5×10^{-2} fb–11 fb, 0.36×10^{-2} fb–82 fb, respectively.

For $k > 0.5$, the mirror quark is heavy enough to decay into T-odd gauge boson plus an ordinary fermion. The branching ratios of the possible two-body modes of the mirror quarks U_H and D_H are discussed in Refs. [13, 26]. The different chain decays of the mirror quark can give different experimental signatures at the LHC, which have been extensively studied. The up- and down-type mirror quarks mainly decay into dW_H^+ and uW_H^-, respectively. For $0.6 \le k \le 1.4$ and $f = 1$ TeV, the values of the branching ratios $\mathrm{Br}(U_H \to dW_H^+)$ and $\mathrm{Br}(D_H \to uW_H^-)$ are all about 57%.[26] To simplify our phenomenological analysis, we only consider the signatures induced by the decay modes uW_H^- and dW_H^+ and take these two decay modes as jW_H, in which j indicates a light-flavor jet u, c, d, or s. Furthermore, we will assume that T-parity is strictly conserved and the T-odd gauge boson B_H can be seen as missing energy.

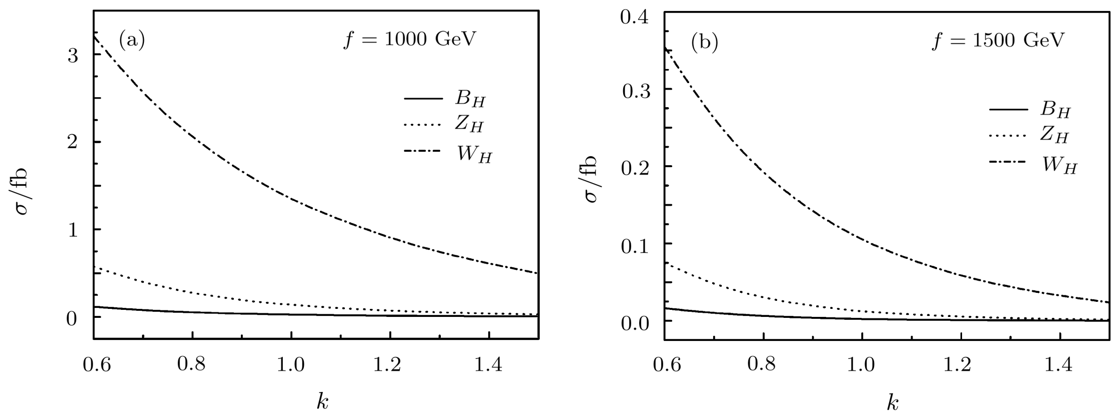

Fig. 3 (a) Same as Fig. 2 but for $f = 1$ TeV; (b) Same as Fig. 2 but for $f = 1.5$ TeV.

From the above discussions, we can see that photoproduction of the mirror quark associated with the T-odd gauge boson at the LHC can give the following final states

$$q\gamma \to Q_H B_H \to jW_H B_H \to jWB_H B_H \to jl\nu_l B_H B_H \,, \tag{9}$$

$$q\gamma \to Q_H Z_H \to jW_H Z_H \to jWHB_H B_H \to jl\nu_l b\bar{b} B_H B_H \,, \tag{10}$$

$$q\gamma \to Q_H W_H^{\pm} \to jW_H^{\pm} W_H^{\mp} \to jW^{\mp} W^{\pm} B_H B_H \to jl^+ l^- \nu_l \nu_i B_H B_H \,. \tag{11}$$

In the above processes, we have assumed that the T-odd gauge bosons W_H and Z_H mainly decay into WB_H and HB_H, respectively. For the Higgs boson mass $M_H \le$ 120 GeV, its dominant decay channel is $H \to b\bar{b}$. In order to ensure the cleanest event signature, only fully leptonic decay modes of the gauge boson W are considered. It is obvious that the chain decay processes (9), (10), and (11) can lead to the $l^{\pm}$+jet+$\not{E}$, $l^{\pm}$+jets+$\not{E}$, and l^+l^-+jet+$\not{E}$ signatures. The production rates for these three kinds of the signatures can be easily estimated by multiplying the overall decay branching ratios to the effective production cross sections for the corresponding processes. For example, the production rate of the $l^{\pm}$ + jet + $\not{E}$ signature can be written as: $\sigma_{B_H} \times \mathrm{Br}\,(Q_H \to jW_H) \times \mathrm{Br}(W_H \to WB_H) \times \mathrm{Br}\,(W \to l\nu_l) \approx \sigma_{B_H} \times 0.57 \times 1 \times 0.32 \approx 0.18\sigma_{B_H}$. The number of the raw signal events generated per year at the LHC are given in Fig. 4, in which we have taken the scale parameter $f = 500$ GeV and the yearly integrated luminosity $\pounds = 100\ \mathrm{fb}^{-1}$. One can see from this figure that there will be several and up to hundreds of these kinds of the signal events to be generated at the LHC per year.

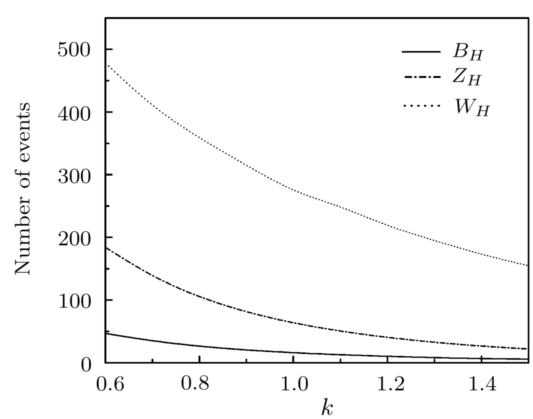

Fig. 4 The number of the raw signal events versus the parameter k for $f = 500$ GeV and $\pounds = 100\ \mathrm{fb}^{-1}$.

In general, the photoproduction signals at the LHC have two kinds of backgrounds: irreducible and reducible backgrounds, which have very similar final states or same final states as the signal, and come from the photo-production processes and the parton-parton interaction processes, respectively. During the phase of the low luminosity, one can use the large rapidity gap (LRG) way to distinguish the photoproduction signal from the reducible backgrounds.[6–9] At high luminosity (general about 100 fb^{-1}), the reducible backgrounds can be suppressed by using the dedicated very forward detectors (VFDs). Applying the acceptance cuts, one can significantly suppress the irreducible backgrounds coming from the SM photoproduction processes, such as $q\gamma \to jW$, $q\gamma \to q'WH$, $q\gamma \to q'W^{\pm}W^{\mp}$, etc. To be certain, a detailed simulation is needed, which is beyond the scope of this paper.

4 Photoproduction of Mirror Quark Associated with a T-Odd Scalar

The LHT model predicts the existence of a complex T-odd triplet scalar Φ with the mass in the range of 350 GeV–1400 GeV for $m_H = 120$ GeV and 500 GeV $\leq f \leq 2000$ GeV. At the leading order, its components $\phi^{\pm}$, ϕ^0, and ϕ^p have the same mass and can be produced via the parton-parton collision processes at the LHC, which have been discussed in Ref. [27]. It has been shown that the production cross sections are much small. Although the T-odd scalar couples to ordinary quark and the mirror quark at the order v^2/f^2,[15] to compare the photoproduction with the partonic production of the T-odd scalars, we consider photoproduction of the T-odd scalars in this section. The relevant Feynman diagrams are shown in Fig. 5.

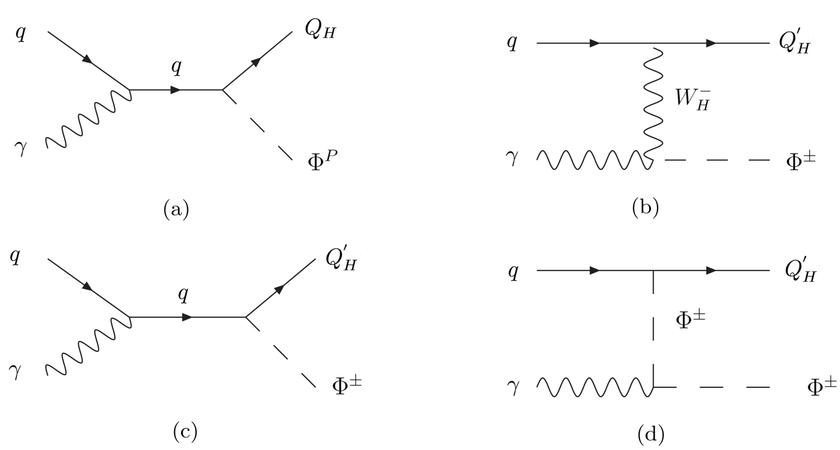

Fig. 5 Feynman diagrams for photoproduction of the mirror quark in association with a T-odd scalar.

Using the relevant Feynman rules given in Ref. [15], the invariant scattering amplitudes for photoproduction of the T-odd scalars can be written as

$$M_{\phi^{\pm}} = -\frac{e^2 V_{ij}}{6\sqrt{2}S_W}\frac{\nu^2}{f}\bar{u}(P_Q)\Big\{\frac{ie\epsilon \not{P}_L}{S_W(\hat{t}_\phi - M_{W_H}^2)} + \frac{MP_L}{2fM_{W_H}}\Big[\frac{q^i(\not{P}_q + \not{P}_\gamma)\not{\epsilon}}{2\hat{s}} + \frac{P_\gamma^\mu \epsilon}{\hat{t}_\phi - M_\Phi^2}\Big]\Big\}u(q)\,, \tag{12}$$

$$M_{\phi^P} = \frac{e^2 q^i V_{ij}}{12\hat{s}}\frac{\nu^2}{f^2}\Big[\frac{1}{\sqrt{10}C_W M_{B_H}} + \frac{1}{\sqrt{2}S_W M_{Z_H}}\Big]M\bar{u}(P_Q)[P_L(\not{P}_q + \not{P}_\gamma)\not{\epsilon}]u(P_q)\,, \tag{13}$$

where $\hat{t}_\phi = (P_Q - P_q)^2$ and $\hat{s} = (P_q + P_\gamma)^2$.

Our numerical results are given in Fig. 6, in which we have plotted the production cross sections as functions of the coupling constant k for the scale parameter $f = 500$ GeV and the other relevant free parameters are taken to be same as Sec. 3. One can see from this figure that the production cross section is indeed very small. In most of the parameter space of the LHT model, the value of the total cross section for photoproduction of the mirror quark in association with a T-odd scalar is smaller than 0.01 fb. However, compared that of partonic production of the T-odd scalar associated the T-odd gauge boson, its background is also very small, which mainly comes from the photon-induced processes.

In most of the parameter space of the LHT model, the T-odd scalars $\phi^{\pm}$ and ϕ^p mainly decay into $W^{\pm}B_H$ and HB_H, respectively. For $m_H = 120$ GeV, $k = 1$, and $f = 1$ TeV, there are $\text{Br}(\phi^{\pm} \to W^{\pm}B_H) \simeq 1$ and $\text{Br}(\phi^p \to HB_H) \simeq 1$. Thus, photoproduction of the T-odd scalars at the LHC can give the following final states:

$$\begin{aligned} q\gamma &\to Q_H\phi^p \to jW_H HB_H \\ &\to jWHB_HB_H \to jl\nu_l b\bar{b}B_HB_H\,, \end{aligned} \tag{14}$$

$$\begin{aligned} q\gamma &\to Q'_H\phi^{\pm} \to jW_H^{\mp}W^{\pm}B_H \\ &\to jW^{\mp}W^{\pm}B_HB_H \to jl^+l^-\nu_l\bar{\nu}_l B_HB_H\,, \end{aligned} \tag{15}$$

which can induce the $l^{\pm} + \text{jets} + \not{E}$ and $l^+l^- + \text{jet} + \not{E}$ signatures. The first kind of signatures is same as that of Eq. (10) and the second is same as that of Eq. (11). Thus, we have to say that it is more difficult to detect the possible signatures of the mirror quark via the subprocess $q\gamma \to Q_H\Phi$ than via the subprosess $q\gamma \to Q'_H W_H$.

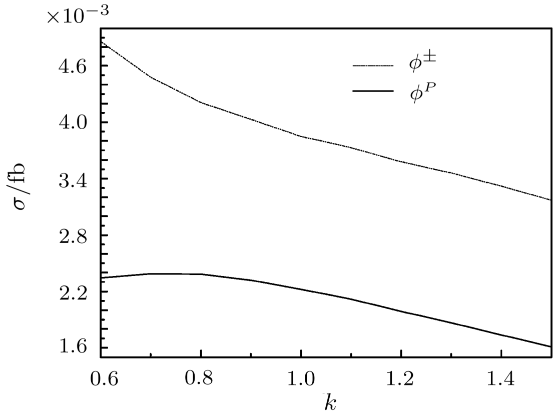

Fig. 6 The production cross sections for the new scalars as function of the coupling constant k for $f = 500$ GeV.

5 Pair Production of Mirror Quarks via γg and $\gamma\gamma$ Collisions

At the LHC, the mirror quarks can be produced in pairs via exchanging the T-odd gauge bosons (B_H and Z_H) and gluon exchange. It has been shown that, as long as their masses are not too large, the mirror quarks can be copiously produced in pairs.[13] However, the mirror quarks can also be produced in pairs via γg and $\gamma\gamma$ collisions at the LHC, which is the main aim of this section. The relevant Feynman diagrams are displayed in Fig. 7, in which Fig. 7(a) is similar to that for the SM process $g\gamma \to t\bar{t}$ and Fig. 7(b) is similar to that for the two-photon production of the supersymmetric pairs or the top quark pairs.

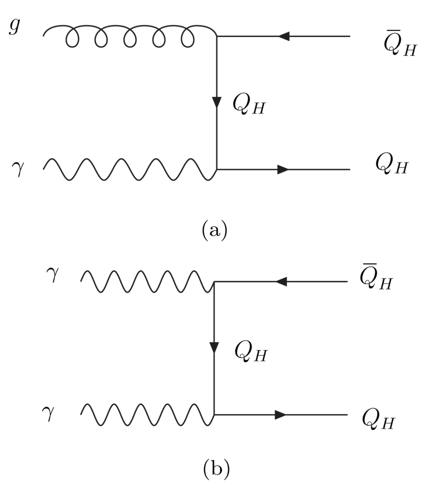

Fig. 7 Feynman diagrams for the photon-induced production of the mirror quark pairs.

It is obvious that the production cross section of the mirror quark pairs is only dependent on the scalar parameter f and the coupling parameter k. In Figs. 8(a) and 8(b) we present the cross sections induced by γg and $\gamma\gamma$ collisions versus the scale parameter f for different values of the parameter k. One can see from these figures that the photon-induced production of the mirror quark pairs is mainly generated by the subprocess $g\gamma \to \bar{Q}_H Q_H$ and the effective cross section $\sigma_{g\gamma}$ is larger than $\sigma_{\gamma\gamma}$ at least by three orders of magnitude. Certainly, this is because the gluon luminosity is much larger than the photon luminosity and the coupling of the gluon to the mirror quarks is stronger than that for the photon. For $k = 0.6$ and 500 GeV $\leq f \leq$ 1500 GeV, the value of the cross section $\sigma_{g\gamma}$ is in the range of 2.1×10^{-3} fb–87.5 fb.

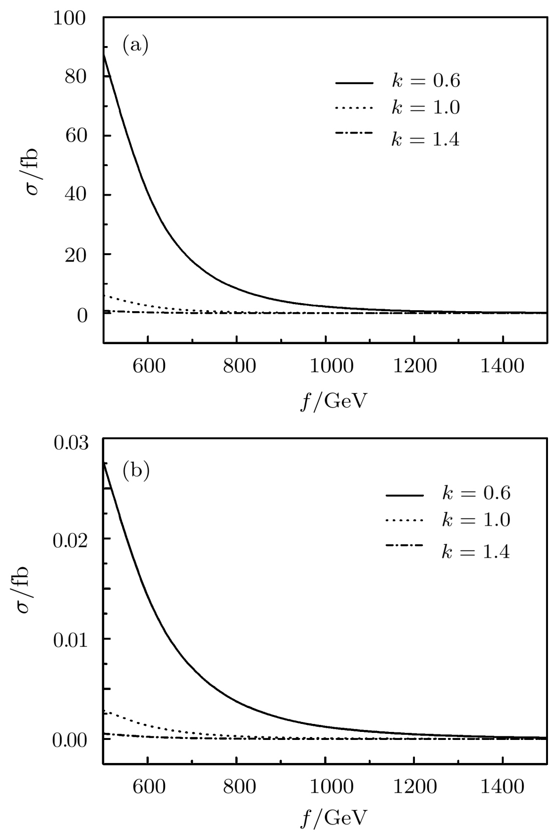

Fig. 8 The production cross sections induced by γg (a) and $\gamma\gamma$ (b) collisions versus f value for different values of k.

If we assume that the mirror quark decays into Wj ($j = u$, c, d, or s) and focus our attention only on the pure leptonic decay modes for the SM gauge boson W, then pair production of the mirror quark can induce the $l^+l^- + \text{jets} + \not{E}$ signature. The total number of this kind of signal events are given in Fig. 9 for $f = 500$ GeV, in which we have taken the integral luminosity $\pounds = 100\ \text{fb}^{-1}$ and $\text{Br}(Q_H \to W_H j) \simeq 57\%$. One can see from this figure that there will be several and up to hundreds of the $l^+l^- + \text{jets} + \not{E}$ signal events to be generated at the LHC.

The reducible SM backgrounds of pair production of the mirror quark via γg and $\gamma\gamma$ interactions mainly come from $t\bar{t}$, which both top quarks decay leptonically, and W^+W^-jj, which the two jets originate from initial-state radiation. Although the reducible background is several orders of magnitude larger than the signal, one expects that it can be reduced to the same level as the irreducible background by using LRG condition and the dedicated VFDs.[6–9] The irreducible backgrounds mainly come from the photon-induced processes $\gamma g \to t\bar{t}$ and $\gamma\gamma \to t\bar{t}$. The ratio of the signal over the square root of the background $R = S/\sqrt{B}$ (called the statistical significance) is given in Fig. 10 in which we have taken $f = 500$ GeV and $\pounds = 100\ \text{fb}^{-1}$. One can see from this figure that, with reasonable values of the free parameters, the values of R can be significantly large.

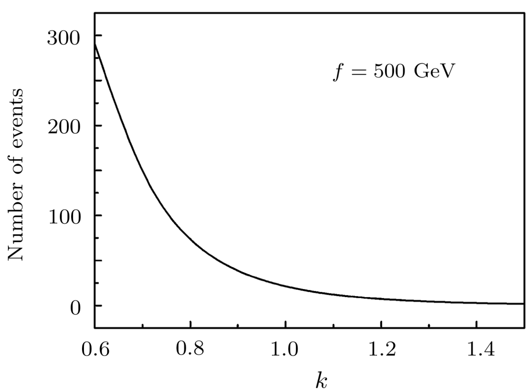

Fig. 9 The number of the $l^+l^- + \text{jet} + \not{E}$ signature events for $f = 500$ GeV and $\pounds = 100\ \text{fb}^{-1}$.

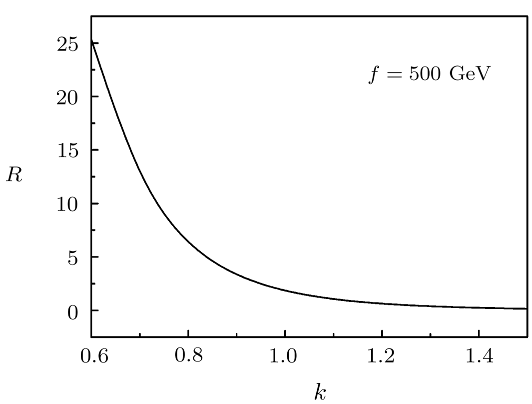

Fig. 10 The statistical significance R as a function of the parameter k for $f = 500$ GeV.

The numerical results of Fig. 10 are obtained in the case of no any cut applied. If we apply acceptance cuts on the final state particles, the irreducible backgrounds can be significantly suppressed and the value of R should be enhanced. Thus, the possible signals of the mirror quarks might be detected via $g\gamma$ collision at the LHC.

6 Conclusions and Discussions

The photon-induced processes at the LHC provide clean experimental conditions due to absence of the proton remnants. Well defined final states can be easily selected and precisely reconstructed. To some extend, the LHC can be considered as a high-energy $\gamma\gamma$ or γp collider, which offers interesting possibilities for studying the electroweak sector and for searching new physics up to TeV scale. One expects that the $\gamma\gamma$ or γp collision at the LHC should give complementary and interesting results for the tests of the SM and for searching of new physics. Thus, considering production of new particles via $\gamma\gamma$ or γp collision at the LHC is very interesting. It will be helpful to detect the possible signatures of new physics models at the LHC.

The LHT model is one of the attractive little Higgs models that is not only consistent with electroweak precision tests but also predicts the existence of the heavy T-odd SU(2) doublet fermions, which are called the mirror fermions of the SM fermions. These new particles might produce the observability signatures in future high energy collider experiments. In this paper, we consider the photon-induced production of the first and second generation mirror quarks and further discuss their possible signatures at the LHC.

The effective production cross sections of the mirror quarks at the LHC via the subprocesses $q\gamma \to Q_H B_H(Z_H)$, $q\gamma \to Q'_H W_H^{\pm}$, $q\gamma \to Q'_H \phi^{\pm}$, $q\gamma \to Q_H \phi^p$, $g\gamma \to \bar{Q}_H Q_H$, and $\gamma\gamma \to \bar{Q}_H Q_H$ are calculated. Our numerical results show that the cross sections for all of these production channels are indeed smaller than those of the partonic processes in most of the parameter space of the LHT model. Furthermore, their values are strongly dependent on the scale parameter f and the coupling parameter k, which decrease quickly as f and k increase. However, as long as the mirror quark is not too heavy, i.e. the parameters f and k are not too large, it can be significantly produced via some of these processes at the LHC. For example, for $0.6 \le k \le 1$ and 500 GeV$\le f \le 1500$ GeV, the effective cross section value of the subprocess $q\gamma \to Q'_H W_H$ is larger than 0.1 fb and can reach 82 fb, and the value of the effective cross section for the subprocess $qg \to \bar{Q}_H Q_H$ is in the range of 2.1×10^{-3} fb $\sim$ 88 fb.

The different chain decay channels of the mirror quark can give different experimental signatures. The possible signatures of the mirror quarks generated from the partonic processes have been studied in Ref. [13]. Considering the dominating decay channels of the mirror quarks, the possible signatures generated by the photon-induced processes are also discussed in this paper. We find that some of the photon-induced processes can produce the same signals as those for the partonic processes. However, because of the clean experimental conditions and the well defined final states, they might be easily detected. For the photon-induced signatures, most of the backgrounds coming from the partonic interactions, called reducible background, can be significantly omitted by using the LRG technique and the dedicated VFDs. The irreducible background generated by $\gamma\gamma$ or γp interaction can be largely suppressed by applying acceptance cuts. Certainly, it should be further studied.

All of our numerical results are obtained in the case of only considering the elastic photon contributions. If the contributions of the inelastic photons are included, the corresponding cross sections are increased by about a factor of three.[2] It is obvious that the irreducible backgrounds are also increased. Furthermore, the strong interactions between protons, the so called rescattering effects, can suppress the photon-induced cross sections, which depends on the invariant mass of the exclusively produced state, such as $Q_H W_H$ or $\bar{Q}_H Q_H$. This kind of correction effects has been ignored in our numerical results. In our simply phenomenological analysis, we have taken the T-odd gauge boson B_H as missing energy. If we assume the T-parity is violated, then B_H can decay into WW and ZZ pairs, which can induce different signatures.

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